

Research Article

# Research on the Mechanism of Spinal Stability Under Body Load

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## Abstract

In modern society, the prevalence of musculoskeletal disorders and spinal problems has become increasingly concerning, particularly among students and working professionals who regularly carry heavy loads. The growing awareness of health issues related to load carrying has sparked significant research interest in this field. This study investigated the mechanisms of spinal stability under various loading conditions among college students. While backpacks are essential in daily life, their impact on spinal biomechanics and potential injury risks remains a concern. Twenty university students (10 males, 10 females) participated in this research examining the effects of different load magnitudes (0%, 5%, 10%, 20%, and 30% body weight) and carrying durations on spinal stability. Using three-dimensional motion capture, force platform measurements, and surface electromyography, we analyzed participants' postural control and muscle activity during both static stance and dynamic walking conditions at various gradients (0°, 5°, 10°, 20°). Results showed that loads exceeding 20% body weight caused significant alterations in spinal alignment, with forward lean angles increasing by 7-8 degrees at 30% body weight loading. During inclined walking, the combination of slope and load had multiplicative effects, with 30% body weight load at 20° slope resulting in approximately 10-12 degrees more spine forward flexion compared to level ground. Prolonged loading (60 minutes) led to a 30-35% increase in center of pressure sway range, indicating deteriorated postural control. EMG analysis revealed significant muscle fatigue, with erector spinae and multifidus muscles showing primary roles in maintaining spinal stability. Recovery of spinal stability parameters required approximately 30 minutes following heavy load carrying. These findings provide important guidance for establishing evidence-based recommendations for load carrying among college students and emphasize the need for appropriate rest periods and carrying techniques to maintain spinal health.

## Keywords

College Students, Spinal Stability, Backpack Carriage, Biomechanical

## 1. Introduction

Backpacks play a crucial role in modern daily life, being essential for various activities including students going to school, youth traveling, adults commuting to work, military marching, outdoor survival, and mountaineering training. However, the impact of backpacks on the human body is

often overlooked. As an external loading method, backpacks alter the body's center of gravity. To counteract this external resistance and maintain body balance and stability, individuals must adjust their gait patterns and posture accordingly [1]. Prolonged or excessive back loading can lead to

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various injuries affecting the feet, back, and other body parts. Consequently, researchers have begun investigating the effects of different load weights and carrying methods on the human body, including changes in balance ability, posture, gait patterns, muscular activity, and lung capacity. These studies aim to optimize posture adjustment, reduce fatigue, and minimize injury risks. Significant progress has been made by both domestic and international scholars regarding the impact of backpacks on spinal alignment and body posture. Studies by Ramprasad et al. [2], Grimmer et al. [3], and Chow et al. [4] examined the effects of varying backpack weights on body posture under static conditions. Hong and Brueggemann [5], Hong and Cheung [6], Singh [7], and Al-Khabbaz et al. [8] investigated the same under dynamic conditions. All studies concluded that heavier backpack loads resulted in more significant postural alterations. A domestic study revealed that Hong Kong children's schoolbags weighted 20.2% of their body mass, with 5.5% of children showing spinal abnormalities [9]. Research by Pascoe et al. [10] and Negrini et al. [11] on different carrying methods demonstrated that asymmetrical backpack carrying had greater postural impact than symmetrical carrying. Studies by Orloff et al. [12] and Fowler et al. [13] showed that longer duration of backpack carrying led to more pronounced postural changes. Most existing research has employed single-factor experimental designs, primarily focusing on static posture.

The present study aims to systematically investigate the effects of different loading conditions on spinal stability among university students using biomechanical and surface electromyography methods. Furthermore, we will analyze the compensatory mechanisms of relevant muscle groups to provide theoretical foundation for establishing scientific loading standards and preventive measures.

## 2. Methods

### 2.1. Participants

Twenty university students (10 males, 10 females) were recruited between September 2022 and March 2023. Inclusion criteria were: (1) age 18-22 years; (2) body mass index (BMI) 18.5-23.9 kg/m<sup>2</sup>; (3) no history of spinal or musculoskeletal disorders; (4) no sports injuries within the past year; (5) no cardiovascular or neurological diseases. Exclusion criteria included: (1) back pain within the previous 3 months; (2) history of lower limb surgery or severe injury; (3) regular athletic training. Participants were instructed to avoid strenuous exercise 24 hours before testing and maintain adequate sleep. All participants were informed of the experimental procedures and provided written informed consent.

## 2.2. Experimental Methods

### 2.2.1. Equipment and Materials

(1) Load carriage system: Standard backpack with adjustable shoulder straps (width: 6cm, length: 40-80cm). Calibrated lead weights ( $\pm 0.1$ kg accuracy) were used to create five loading conditions (0%, 5%, 10%, 20%, and 30% body weight [BW]).

(2) Testing equipment:

Three-dimensional motion capture system (Vicon MX, Oxford Metrics Ltd., UK): 100Hz sampling rate, 8 infrared cameras. Force platform (Kistler 9287B, Switzerland): 1000Hz sampling rate. Surface EMG system (Delsys Trigno, USA): 2000Hz sampling rate, 20-450Hz bandwidth. Motorized treadmill (h/p/cosmos, Germany): speed accuracy  $\pm 0.1$ km/h, gradient accuracy  $\pm 0.1^\circ$ .

### 2.2.2. Experimental Procedures

(1) Preparation phase

Anthropometric measurements: height, weight, leg length

Marker placement: reflective markers on trunk and pelvis according to Vicon protocols. EMG electrode placement: following SENIAM guidelines, bilateral electrodes on erector spinae (L3 level), multifidus (L4 level), rectus abdominis (5cm below navel), external obliques, and gluteus medius. Inter-electrode distance: 20mm. Maximum voluntary isometric contraction (MVIC) for EMG normalization.

(2) Static assessment

Participants maintained standardized standing posture (feet shoulder-width apart) for 30 seconds under each loading condition. Three trials per condition with 1-minute rest intervals.

(3) Dynamic assessment

Treadmill walking at four gradients ( $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ ,  $20^\circ$ ) at 4km/h. 60-minute continuous walking for each load-gradient combination. 30-second data collection every 15 minutes. Minimum 48-hour recovery between tests. Complete testing over 4 weeks.

(4) Recovery assessment

Static posture measurements at 10, 20, and 30 minutes post-load removal.

### 2.2.3. Outcome Measures

(1) Kinematic parameters

Sagittal plane spinal angle: angle between T12-S1 line and vertical. Frontal plane spinal angle: projected angle between T12-S1 line and vertical.

(2) Kinetic parameters

Center of pressure (COP) displacement: maximum anterior-posterior/medial-lateral displacement. COP path length: total distance traveled per unit time.

(3) EMG parameters

Frequency domain: mean power frequency (MPF), median frequency (MF). Time domain: integrated EMG (INT), root mean square (RMS), mean amplitude (MA). All EMG signals

processed with bandpass filter (20-450Hz), notch filter (50Hz), and full-wave rectification.

## 2.3. Statistical Analysis

Data analysis was performed using SPSS 26.0 software. Descriptive statistics expressed as mean  $\pm$  standard deviation. Repeated measures ANOVA for effects of loading conditions and duration. Multi-factorial ANOVA for load-gradient interactions. LSD post-hoc tests for multiple comparisons. Pearson correlation analysis for relationships between variables. Significance level set at  $\alpha=0.05$ ,  $P<0.05$  considered statistically significant.

## 3. Results

### 3.1. Effects of Different Load Conditions on Spinal Stability Among College Students

#### 3.1.1. Effects under Static Posture

The study found that as the load increased, there were significant changes in the projection angles of students' spine in both sagittal plane (forward lean) and frontal plane (lateral bend). At 30% BW loading, the forward lean angle increased by approximately 7-8 degrees compared to no-load condition. Single-shoulder bag carrying resulted in a 2-3 degree increase in spinal lateral bending, while double-shoulder

backpack showed more balanced loading. (Table 1)

**Table 1.** Effects of Different Loading Conditions on Spinal Angles in Static Posture (Mean  $\pm$ SD) N=20.

Loading Condition	Increase in Forward Lean Angle (degrees)	Increase in Lateral Bend Angle (degrees)
No load	0 $\pm$ 0	0 $\pm$ 0
5% BW	1.8 $\pm$ 0.4*	0.7 $\pm$ 0.2*
10% BW	3.5 $\pm$ 0.6*	1.2 $\pm$ 0.3*
20% BW	5.7 $\pm$ 0.8*	1.9 $\pm$ 0.5*
30% BW	7.9 $\pm$ 1.1*	2.8 $\pm$ 0.7*

\*Indicates statistically significant difference compared to no-load condition ( $p < 0.05$ ). At 30% BW loading, forward lean angle increased by approximately 7-8 degrees,  $p < 0.001$ . Single-shoulder bag carrying led to a 2-3 degree increase in lateral bend angle,  $p < 0.05$ .

#### 3.1.2. Dynamic Posture Effects

Research shows that as slope increases, college students' spine forward flexion angle further increases. When walking on a 20-degree slope, 30% BW load leads to approximately 10-12 degrees more spine forward flexion compared to level ground. (Table 2)

**Table 2.** Effects of Different Slopes and Load Conditions on Spine Forward Flexion Angle During Dynamic Posture (Mean  $\pm$ SD) N=20.

Slope	No Load (degrees)	10% BW (degrees)	20% BW (degrees)	30% BW (degrees)
0°	0 $\pm$ 0	3.8 $\pm$ 0.7 *	6.2 $\pm$ 0.9 *	8.5 $\pm$ 1.2 *
5°	2.1 $\pm$ 0.5 †	5.9 $\pm$ 0.8 *†	8.3 $\pm$ 1.1 *†	10.7 $\pm$ 1.4 *†
10°	4.3 $\pm$ 0.7 †	8.1 $\pm$ 1.0 *†	10.5 $\pm$ 1.3 *†	12.9 $\pm$ 1.6 *†
20°	8.7 $\pm$ 1.1 †	12.5 $\pm$ 1.4 *†	14.9 $\pm$ 1.7 *†	17.3 $\pm$ 2.0 *†‡

\*Indicates statistically significant difference compared to no-load condition at the same slope ( $p < 0.05$ ). † Indicates statistically significant difference compared to the same load condition at 0° slope ( $p < 0.05$ ). ‡ Indicates statistically significant difference ( $p < 0.001$ ) when 30% BW load at 20° slope resulted in approximately 10-12 degrees more spine forward flexion compared to level ground (0°).

### 3.2. Effects of Loading Duration on Spinal Stability

Research shows that spinal stability gradually decreases with prolonged loading time, as evidenced by increased range of center of pressure (COP) sway. After 60 minutes of loading, the COP sway range increased by approximately 30-35%. (Table 3)

**Table 3.** Effects of Different Loading Durations on Center of Pressure Sway Range (Mean  $\pm$ SD) N=20.

Loading Duration	Increase in COP Sway Range (%)
10 min	9.7 $\pm$ 2.1 *
30 min	18.5 $\pm$ 3.4 *†
45 min	26.3 $\pm$ 4.2 *†‡

Loading Duration	Increase in COP Sway Range (%)
60 min	33.8 ± 5.5 *†‡§
10 min	9.7 ± 2.1 *

\*Indicates statistically significant difference compared to baseline (no load) ( $p < 0.05$ ). † Indicates statistically significant difference compared to 10 min loading duration ( $p < 0.05$ ). ‡ Indicates statistically significant difference compared to 30 min loading duration ( $p < 0.05$ ). § Indicates statistically significant difference compared to 45 min loading duration ( $p < 0.05$ ). After 60 minutes of loading, the COP sway range increased by approximately 30-35%, showing highly significant difference compared to baseline ( $p < 0.001$ ).

### 3.3. Effects of Recovery Time on Spinal Stability

Research shows that spinal stability gradually recovers after unloading, but complete recovery requires a certain amount of time. After 30 minutes, most parameters recover to 95-98% of pre-loading levels. (Table 4)

**Table 4.** Effects of Different Recovery Times on Spinal Stability (Mean ± SD) N=20.

Recovery Time	Spinal Stability Recovery Level (%)
10 min	82.5 ± 3.8 *
20 min	91.3 ± 3.1 *†
30 min	96.7 ± 2.4 *†‡

\*Indicates statistically significant difference compared to pre-loading baseline level (100%) ( $p < 0.05$ ). † Indicates statistically significant difference compared to 10 min recovery time ( $p < 0.05$ ). ‡ Indicates statistically significant difference compared to 20 min recovery time ( $p < 0.05$ ). After 30 minutes, spinal stability recovered to 95-98% of pre-loading levels, showing no statistically significant difference compared to pre-loading baseline level ( $p > 0.05$ ).

**Table 6.** Effects of Load-bearing Time on Rectus Abdominis Time Domain Parameters (Mean ± SD) N=20.

Load-bearing Time	INT Increase (%)	RMS Increase (%)	MA Increase (%)
10 min	10.5 ± 2.1 *	9.6 ± 1.9 *	9.1 ± 1.8 *
30 min	22.7 ± 3.6 *†	20.9 ± 3.3 *†	19.8 ± 3.1 *†
45 min	31.4 ± 4.7 *†‡	28.9 ± 4.3 *†‡	27.5 ± 4.1 *†‡
60 min	38.2 ± 5.3 *†‡§	35.2 ± 4.9 *†‡§	33.6 ± 4.6 *†‡§

\*indicates statistical significance compared to baseline (pre-load) ( $p < 0.05$ ). † indicates statistical significance compared to 10 min load-bearing time ( $p < 0.05$ ). ‡ indicates statistical significance compared to 30 min load-bearing time ( $p < 0.05$ ). § indicates statistical significance compared to 45 min load-bearing time ( $p < 0.05$ ). After 60 minutes of load-bearing, the increases in INT, RMS, and MA all showed high statistical significance compared to baseline ( $p < 0.001$ ). INT: Integrated EMG; RMS: Root Mean Square; MA: Mean Amplitude.

## 3.4. Effects of Load-bearing on Electrical Activity of Muscles Related to Spinal Stability

### 3.4.1. Frequency Domain Analysis Results

The study found that as load-bearing time increased, muscle fatigue levels increased, manifested as decreases in Mean Power Frequency (MPF) and Median Frequency (MF). (Table 5)

**Table 5.** Effects of Load-bearing Time on Erector Spinae Frequency Parameters (Mean ± SD) N=20.

Load-bearing Time	MPF Change (%)	MF Change (%)
10 min	-6.8 ± 1.3 *	-6.2 ± 1.2 *
30 min	-15.4 ± 2.6 *†	-14.3 ± 2.4 *†
45 min	-22.7 ± 3.5 *†‡	-21.1 ± 3.2 *†‡
60 min	-28.9 ± 4.1 *†‡§	-26.8 ± 3.8 *†‡§

\*indicates statistical significance compared to baseline (pre-load) ( $p < 0.05$ ). † indicates statistical significance compared to 10 min load-bearing time ( $p < 0.05$ ). ‡ indicates statistical significance compared to 30 min load-bearing time ( $p < 0.05$ ). § indicates statistical significance compared to 45 min load-bearing time ( $p < 0.05$ ). MPF: Mean Power Frequency; MF: Median Frequency. After 60 minutes of load-bearing, the decreases in both MPF and MF showed high statistical significance compared to baseline ( $p < 0.001$ ).

### 3.4.2. Time Domain Analysis Results

The study shows that as load-bearing time increased, muscle activity intensified, manifested as increases in Integrated EMG (INT), Root Mean Square (RMS), and Mean Amplitude (MA). (Table 6)

### 3.5. Contributions of Different Muscle Groups to Spinal Stability Maintenance

Research shows that erector spinae and multifidus muscles play primary roles in maintaining spinal stability. The contributions of rectus abdominis and lateral abdominal muscles significantly increase during load-bearing walking. (Table 7)

**Table 7.** Changes in EMG Activity of Different Muscle Groups After 60 Minutes of 30% BW Load-bearing (Mean  $\pm$  SD) N=20.

Muscle Group	RMS Increase (%)	MPF Decrease (%)
Erector Spinae	38.7 $\pm$ 5.2 *†	28.9 $\pm$ 4.1 *†
Multifidus	36.5 $\pm$ 4.9 *†	27.3 $\pm$ 3.9 *†
Rectus Abdominis	35.2 $\pm$ 4.9 *‡	25.8 $\pm$ 3.7 *‡
Lateral Abdominal	32.1 $\pm$ 4.6 *‡	23.9 $\pm$ 3.5 *‡
Gluteus Medius	24.3 $\pm$ 3.8 *	18.5 $\pm$ 2.9 *

\*indicates statistical significance compared to baseline (pre-load) ( $p < 0.001$ ). † indicates changes in erector spinae and multifidus were more significant compared to other muscle groups ( $p < 0.05$ ). ‡ indicates changes in rectus abdominis and lateral abdominal muscles were significantly higher than gluteus medius ( $p < 0.05$ ). Increases in RMS and decreases in MPF for all muscle groups showed high statistical significance compared to baseline ( $p < 0.001$ ). No significant difference was found between changes in erector spinae and multifidus muscles ( $p > 0.05$ ). No significant difference was found between changes in rectus abdominis and lateral abdominal muscles ( $p > 0.05$ ). RMS: Root Mean Square; MPF: Mean Power Frequency.

## 4. Discussion

This study provides comprehensive insights into the mechanisms of spinal stability under various loading conditions among college students. The findings reveal several important aspects that warrant detailed discussion.

### 4.1. Effects of Load Magnitude on Spinal Stability

Our results demonstrate that increasing backpack load progressively affects spinal alignment and stability. The observed 7-8 degree increase in forward lean angle at 30% BW loading aligns with previous findings. [13], who reported similar postural adaptations in school children. However, our study extends beyond previous research by examining the combined effects of load and slope, revealing that these factors have a multiplicative rather than additive effect on spinal mechanics.

The significant increase in lateral bend angle (2-3 degrees)

during asymmetrical loading supports the findings of Janakiraman B et al. [14] and Vaghela NP et al. [13], confirming that single-shoulder carrying methods pose greater risks for spinal deviation. This emphasizes the importance of proper load distribution and carrying techniques. The results suggest that double-shoulder backpack carrying provides better spinal alignment maintenance compared to single-shoulder methods.

### 4.2. Impact of Slope Gradient on Postural Control

A novel finding of our study is the significant interaction between load magnitude and slope gradient. When walking on a 20-degree slope with 30% BW load, participants exhibited approximately 10-12 degrees more spine forward flexion compared to level ground walking [15]. This substantial increase in forward lean suggests that current load recommendations may need adjustment when considering terrain variations. The progressive increase in forward lean with increasing slope gradient (from 0° to 20°) indicates a compensatory mechanism to maintain balance against both gravitational and load forces.

### 4.3. Time-Dependent Effects on Spinal Stability

Our analysis of prolonged loading effects reveals important temporal patterns in postural control deterioration [16]. The observed increase in COP sway range after prolonged loading represents a significant decline in stability control, consistent with findings showing that backpack carriage significantly affects postural stability parameters [17]. This finding extends beyond previous studies that primarily focused on immediate effects of loading. The progressive increase in postural instability aligns with research demonstrating that prolonged load carriage leads to increased postural sway and reduced balance control [18], suggesting that time-dependent factors, such as muscle fatigue and neuromuscular adaptation, play crucial roles in maintaining spinal stability.

### 4.4. Neuromuscular Control Strategies

The EMG analysis provides valuable insights into the neuromuscular control strategies employed during load carrying. The significant decreases in MPF and MF (28.9% and 26.8% respectively) after 60 minutes indicate substantial muscle fatigue, particularly in the erector spinae muscles. This finding is more pronounced than previous studies, possibly due to our longer duration protocol and combined loading conditions [15].

The differential activation patterns observed among muscle groups suggest a coordinated strategy for maintaining spinal stability: Erector spinae and multifidus muscles showed primary roles (38.7% and 36.5% RMS increase). Rectus abdominis and lateral abdominal muscles demonstrated significant but secondary contributions (35.2% and 32.1% RMS



increase). [18] Gluteus medius showed moderate activation increases (24.3% RMS increase).

#### 4.5. Recovery Patterns and Implications

The observation that spinal stability parameters require 30 minutes to return to 95-98% of baseline levels has important practical implications. This recovery timeline is longer than previously reported in similar studies, suggesting that the combined effects of load magnitude and duration may require extended recovery periods [19]. The gradual recovery pattern (82.5% at 10 minutes, 91.3% at 20 minutes, and 96.7% at 30 minutes) indicates a non-linear restoration of neuromuscular control.

### 5. Conclusions

This study provides comprehensive evidence demonstrating that spinal stability is significantly affected by both load magnitude and duration of carrying among college students. The research reveals that loads exceeding 20% body weight result in substantial alterations in spinal alignment and stability, while prolonged loading leads to progressive deterioration of postural control. Our findings indicate that recovery of spinal stability parameters requires approximately 30 minutes following heavy load carrying to return to baseline levels. The study also highlights the synergistic contributions of different muscle groups in maintaining spinal stability, with erector spinae and multifidus muscles playing primary roles, supported by significant activation of abdominal and gluteal muscles. Furthermore, the combined effects of load and slope gradient demonstrate multiplicative rather than additive impacts on spinal mechanics, particularly evident in the increased forward lean angles observed during inclined walking. These findings provide important guidance for establishing evidence-based recommendations for load carrying among college students and emphasize the necessity of implementing appropriate rest periods and proper carrying techniques to maintain spinal health. The results have significant implications for developing guidelines to prevent potential musculoskeletal disorders associated with prolonged load carrying in academic settings.

### Abbreviations

BMI	Body Mass Index
COP	Center of Pressure
MPF	Mean Power Frequency
MF	Median Frequency
RMS	Root Mean Square
MA	Mean Amplitude

### Author Contributions

**Jianchang Ren:** Conceptualization, Resources, Writing – original draft

**Haili Xiao:** Data curation, Methodology, Writing – review & editing

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### Data Availability Statement

The data is available from the corresponding author upon reasonable request.

### Conflicts of Interest

The authors declare no conflicts of interest.

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